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Requirements of a Coherent Laser Pulse-Doppler Radar*

G. BIERNSON†, SENIOR MEMBER, IRE, AND R. F. LUCY†, MEMBER, IRE

***Summary*—The use of coherent detection can theoretically allow optical radar systems employing laser transmitters to achieve considerably improved receiver sensitivity, particularly in conditions of high background radiation. However, there are many practical factors that can limit sensitivity in coherent optical detection, which are described. It is shown that to achieve an efficient coherent optical radar, one would generally like a pulse width less than 10 μsec and a spectral line width less than 10 Mc.**

I. Introduction

THE DEVELOPMENT of the laser, which generates a coherent light signal, provides the potentiality of practical optical radar systems. One of the advantages of coherent light is that it allows the beam to be very narrow. However, an even more important advantage for the optical radar application is that it allows the receiver to employ coherent detection and thereby to achieve considerably greater sensitivity in daylight operation. The purpose of this paper is to describe the requirements and performance of coherent optical detection in an optical radar application, and to compare the performance with that achieved by noncoherent detection.

A photodetector acts as a square-law detector, providing an electrical output power proportional to the square of the input optical power. In a conventional optical receiver, the received optical signal is fed alone into the detector, and noncoherent detection is performed. In a coherent optical receiver, the received optical signal is summed with a coherent optical reference (called the local-oscillator reference) and the summed optical signal is fed to the photodetector. The squaring process of the detector effectively multiplies the received signal and the local-oscillator reference together, and the bandwidth narrowing of the subsequent amplifier effectively integrates the resultant product. This combination of multiplication and integration in coherent detection performs a cross correlation, which allows the receiver to achieve considerably greater sensitivity than one employing noncoherent detection.

If the local-oscillator reference is a pure sinusoid and its power can be made arbitrarily large, the effects of background optical power and dark current in the detector become negligible, and the optical receiver is able to achieve detection characteristics given by

$$\frac{P_{so}}{P_{no}} = \frac{QP_s}{(h\nu)\Delta f} \qquad (1)$$

where (P_{so}/P_{no}) is the signal-to-noise power ratio out of the receiver, Δf is the receiver noise bandwidth, P_s is the received optical power, Q is the quantum efficiency of the detector, and $h\nu$ is the energy per photon (Planck's constant h times optical frequency ν).

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† Applied Research Laboratory, Sylvania Electronics System, A Division of Sylvania Electric Products, Inc., Waltham, Mass.

At present, there are two optical wavelengths which are of particular interest: 6943 Å for the ruby laser and 11,500 Å for the gas laser. At these wavelengths, the energy per photon is

$$h\nu = 2.85 \times 10^{-19} \text{ joules} \quad \text{(Ruby, 6943 Å)}, \tag{2}$$

$$h\nu = 1.72 \times 10^{-19} \text{ joules} \quad \text{(Gas, 11,500 Å)}. \tag{3}$$

It is desirable to compare the sensitivity of a coherent optical receiver to that of a microwave receiver. For a microwave radar the expression equivalent to (1) is

$$\frac{P_{so}}{P_{no}} = \frac{P_s}{KT_{eff}\Delta f} \tag{4}$$

where K is Boltzman's constant and T_{eff} is the effective noise temperature of the receiver. Thus, for unity quantum efficiency Q, the energy per photon $h\nu$ is equivalent to KT_{eff}. Setting $h\nu$ equal to KT_{eff} gives the following ideal noise temperatures for optical receivers:

$$T_{eff} = 20{,}800°\text{K} \quad \text{(Ruby, 6943 Å)}, \tag{5}$$

$$T_{eff} = 11{,}500°\text{K} \quad \text{(Gas, 11,500 Å)}. \tag{6}$$

Thus, even if ideal detection is achieved, an optical receiver is very noisy in comparison with microwave receivers.

On the other hand, quantum efficiencies of photodetectors are generally much less than unity. The best values achieved to date for photomissive surfaces at the wavelengths of the ruby and gas lasers are as follows:

$$Q = 0.04 \text{ for Type S20 Photosurface at 6943 Å}, \tag{7}$$

$$Q = 1.5 \times 10^{-4} \text{ for Type S1 Photosurface at 11,500 Å}. \tag{8}$$

The ideal noise temperatures given in (5) and (6) should be divided by these quantum efficiencies to obtain the noise temperatures now achievable with photoemissive detectors. Dividing these resultant effective noise temperatures by room temperature (291°K) gives the noise figures NF of the practical optical receivers, which are,

$$\text{NF} = 32.5 \text{ db (Ruby, 9643 Å)}, \tag{9}$$

$$\text{NF} = 54.5 \text{ db (Gas, 11,500 Å)}. \tag{10}$$

These are very high in comparison to microwave receivers. Semiconductor photodetectors promise quantum efficiencies close to unity, but now have too slow a speed of response to be generally desirable for a coherent laser receiver. This point will be discussed later.

To minimize the signal required to achieve a given signal-to-noise ratio at the receiver output, (1) shows that the receiver noise bandwidth Δf should be made as small as possible. However there are important effects that place a lower limit on the value of Δf, which are as follows:

1) Spread of spectral line due to pulsing,
2) Spread of spectral line due to lack of perfect coherence of the optical signal,
3) The effect of Doppler shift.

The most fundamental limitation is point 1). Points 2) and 3) are discussed later.

Fig. 1 shows the voltage spectrum of a signal at frequency F_0 modulated by a rectangular pulse of width τ. The pulse modulation smears the signal in frequency. In order to pass a reasonable amount of the pulse power, the receiver noise bandwidth Δf should be at least equal to $1/\tau$:

$$\Delta f \geqq 1/\tau. \tag{11}$$

To achieve maximum sensitivity, Δf should be equal to $1/\tau$. Set $\Delta f = 1/\tau$ in (1) and solve for P_s.

$$P_s \geq (P_{so}/P_{no})h\nu/Q\tau. \tag{12}$$

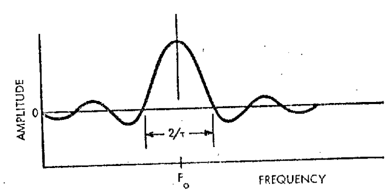

Fig. 1—Voltage spectrum of pulse-modulated signal of frequency F_0 and pulse width τ.

This equation is not strictly correct, because it ignores the loss of signal power through the filter. However, for the purpose of simplicity, this small discrepancy will be ignored. It can readily be accounted for by specifying a somewhat larger value for the output signal-to-noise ratio P_{so}/P_{no} at the threshold.

The received signal energy E_s is equal to $P_s\tau_s$ which by (12) is equal to the following for optimum detection:

$$E_s = (P_{so}/P_{no})(h\nu)/Q. \tag{13}$$

If Q could be made unity, (13) shows that the number of photons (of energy $h\nu$) required for detection is ideally equal to the signal-to-noise power ratio (P_{so}/P_{no}) required at the threshold. Since the signal-to-noise ratio at the threshold must be at least 10 db, the system must receive at least 10 photons in order to achieve a reasonably high probability of false alarm and low probability of false dismissal, for an ideal detector. With a practical photoemissive detector available today ($Q=0.04$) the system must receive at least 250 photons at the ruby laser frequency.

If noncoherent detection is employed, the signal power that can be detected is given by the following:

$$P_{s(nc)} = \sqrt{2P_n P_{s(c)}}, \tag{14}$$

where

P_n = effective optical noise power on detector,
$P_{s(c)}$ = signal power detectable by coherent detection,
$P_{s(nc)}$ = signal power detectable by noncoherent detection.

The noise power P_n represents the power in the background radiation that falls on the detector plus the effect of the detector dark current in terms of the equivalent optical power. The loss $L_{(nc)}$ produced by noncoherent detection is

$$L_{(nc)} = \frac{P_{s(nc)}}{P_{s(c)}} = \sqrt{\frac{2P_n}{P_{s(c)}}} = \sqrt{\frac{2P_n\tau}{E_{s(c)}}} \tag{15}$$

where $E_{s(c)}$ is the signal energy required for coherent detection, which was given in (13).

Eq. (15) shows that in order to minimize the loss when noncoherent detection is performed, one should 1) make the pulse length τ as short as possible and 2) make the optical noise P_n as small as possible. The dark current component of noise power can be kept small by cooling the detector in liquid nitrogen. If the detector operates at night, the background optical power can be kept small. If the pulse is made very short, the loss with noncoherent detection under such conditions is small. However, under daylight conditions, there is considerable loss in sensitivity with noncoherent detection.

When noncoherent detection is performed, the dark current of the photodetector is very important. However, with coherent detection, the dark current can be ignored as long as its effective power is small in comparison to the local-oscillator power. With coherent detection, the quantum efficiency is the parameter that is of primary importance. It may well be that better photosurfaces can be achieved in coherent-detection optical receivers by sacrificing low dark current to achieve higher quantum efficiency.

II. Laser Radar Design

Let us now consider what is required in terms of equipment and equipment performance to realize an effective coherent laser radar.

Fig. 2 gives a block diagram of a coherent laser radar. A CW laser oscillator 1) generates a signal at optical frequency F_o. This is fed to a pulse-modulated amplifier 2) which generates a pulsed optical signal of carrier frequency F_o. The target echo frequency is shifted from the transmitted frequency F_o by the Doppler shift F_d, and so has a carrier frequency of (F_o+F_d). An optical frequency translator 3) is often needed to shift the local-oscillator frequency from the frequency F_o of the CW laser oscillator by an offset frequency F_x. Thus the local-oscillator signal has a frequency of (F_o+F_x). The local oscillator signal and target echo signal are summed together optically 4) and fed to the photodetector 5). The photodetector gives as an output a signal at the difference between the target echo frequency (F_o+F_d) and the local-oscillator frequency (F_o+F_x), which is thus at the frequency $|F_d-F_x|$. This signal is fed to the receiver.

The target Doppler frequency shift F_d is given by the following expression:

$$F_d = 2V/\lambda \tag{16}$$

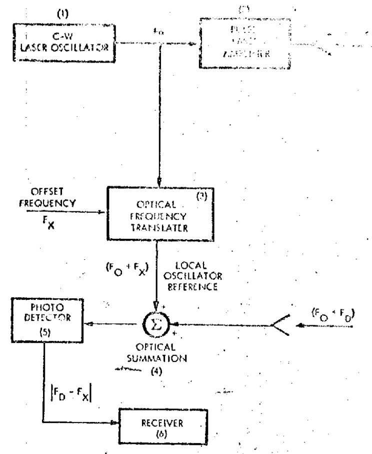

Fig. 2—Block diagram of a coherent optical radar.

where V is the relative closing velocity and λ is the wavelength of the optical signal. For the ruby laser wavelength 6943 Å, the Doppler shift is 875 kc/ft/sec (or in round numbers 1 Mc/ft/sec).

It appears that laser radar systems may be quite useful in space vehicle applications. Relative velocities for such applications may be as high as 10 miles per sec, which represents the relative speed between two low-altitude satellites traveling in opposite directions. The Doppler shift at the ruby laser wavelength for this extreme condition is 50 Gc. Thus for space vehicle applications a coherent laser radar would have to operate over frequencies from 0 to 50 Gc.

If a frequency translator were not used, the photodetector would have to pass the Doppler frequency which could be as high as 50 Gc for a space vehicle application. By using a frequency translator, the photodetector need merely pass the difference between the Doppler frequency F_d and the offset frequency F_x, which can be relatively small.

The most convenient detector available today is the photomultiplier tube. Commercial units are capable of passing 300 Mc, but much wider bandwidths appear to be possible. Another approach is the TWT phototube, which now can pass frequencies from 2 to 4 Gc. Semiconductor photodetectors promise much higher quantum efficiencies but appear to be limited to much lower bandwidths.

Although the frequency translators allow the detector to operate with a bandwidth much less than the Doppler shift, it is usually desirable that the detector have the widest possible bandwidth in order that it can simultaneously examine the largest possible region of Doppler frequencies during search.

The receiver that follows the photodetector will generally have a large number of parallel frequency channels to allow it to achieve a relatively narrow receiver noise bandwidth Δf yet also be able to cover the full Doppler frequency region passed by the photodetector. The narrower the noise bandwidth Δf, the greater number of channels are required. Therefore, practical considerations place a lower limit on the allowable filter bandwidth.

It appears that the receiver bandwidth Δf may typically be between 1 Mc and 100 Mc. Since 1 Mc corresponds to a speed resolution of 1 ft/sec, a bandwidth below 1 Mc would lead to very difficult tracking problems, and would require an excessive number of receiver channels during search. With a 10-Mc bandwidth, 30 filters would be required to cover the 300-Mc region of the photodetector, which appears reasonable. With an TWT phototube, which has a 2000-Mc bandwidth, a wider filter bandwidth may be desirable. On the other hand, if the radar is used for ground tracking applications, where Doppler shifts are small, a bandwidth of 1 Mc might be used.

We will thus assume a receiver bandwidth Δf of 10 Mc as a typical number. To achieve optimum detection, the pulse width τ should be equal to $1/\Delta f$ or 0.1 μsec. Such a laser radar system would achieve a speed resolution of 11 ft/sec and a range resolution of 50 ft. It also would have very high angular resolution. Thus a laser radar is capable of achieving very high resolution in speed, range and angle. In contrast, a microwave radar has relatively poor angular resolution; and can achieve range resolution without speed resolution (in a pulse radar), or speed resolution without range resolution (in a Doppler radar).

The laser radar has much greater resolution capability than a microwave radar, but is far inferior in search. The poor search capability is due to 1) its high noise figure, 2) the generally smaller capture area of its receive aperture, 3) the low efficiency of lasers. For this reason laser radars will probably usually be operated in conjunction with other equipment (often microwave radar), which will perform the coarse search function. The laser radar will generally search over only a relatively small region of range, speed, and angle.

It has been shown that we would like to operate with a receiver bandwidth Δf of the order of 10 Mc with a pulse width τ of 0.1 μsec. This gives the optimum detection condition $\tau\Delta f=1$. However, as will be shown we can tolerate without excessive degradation a value of $\tau\Delta f$ up to 100, which would allow a 10-μsec pulse width for a 10-Mc bandwidth. Let us now examine the capabilities of present lasers to satisfy these requirements.

A serious problem of lasers is that they tend to oscillate in a number of modes to deliver a series of frequencies which are separate by the resonant frequency of the cavity, which is typically about 1.7 Gc. In order for efficient coherent detection to be performed, the CW laser oscillator and pulsed laser amplifier must be able to oscillate in a single mode. It is desirable that the line width be less than 10 Mc, although a somewhat wider width can probably be tolerated.

The gas laser is able to oscillate in a single mode in a CW fashion, but is not capable of generating short pulses of high peak powers. Thus it cannot now satisfy our requirement of a pulse length shorter than 10 μsec.

In contrast, the ruby laser can generate short pulses of high peak powers, but is very bad from a multimode point of view. It also tends to generate very erratic pulse trains, and does not oscillate readily in a CW fashion (which is needed to satisfy the CW oscillator requirements). Unfortunately gas and ruby lasers cannot be used together in a system because they operate at different optical wavelengths.

Thus there are many practical problems in laser design that must be solved before the coherent laser radar system can be realized. However, the purpose of this paper is to concentrate on the requirements of such a system and not the means of designing a laser to satisfy these requirements.

III. General Discussion of Coherent Detection

A detailed analysis of coherent and noncoherent detection in a photodetector is given in Section IV. This section presents a simplified analysis of the difference between coherent and noncoherent detection, and summarizes the performance achievable by coherent detection.

A. Simplified Analysis of Coherent and Noncoherent Detection

In a noncoherent detector, the signal is fed into a rectifying device. Since this device has no negative output, its response can be expressed as an even infinite series, as follows

$$e_o = ae_i^2 + be_i^4 + ce_i^6 + \cdots. \tag{17}$$

Generally one can ignore the higher order terms and get a good approximation of the action by assuming that $e_o=ae_i^2$, *i.e.*, that the rectifier is a square-law detector. A photodetector is an ideal square law device in which the higher terms of (17) are not present.

In a square-law detector, the output signal-plus-noise (s_o+n_o) is related as follows to the input signal-plus-noise (s_i+n_i):

$$s_o + n_o = a(s_i + n_i)^2 = a(s_i^2 + 2s_in_i + n_i^2) \tag{18}$$

where a is a constant, the output signal is (s_i^2), and the output noise is $(2s_in_i+n_i^2)$. The noise consists of two terms: one (n_i^2) due to beats between the noise components, and the other $2s_in_i$ due to beats between the signal and noise. If the input signal-to-noise ratio is much less than unity, n_i^2 is much greater than $2s_in_i$, and so the output noise and signal are approximately

$$s_o = as_i^2, \tag{19}$$

$$n_o \cong an_i^2 \quad \text{for} \quad (P_{si}/P_{ni}) \ll 1. \tag{20}$$